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DETECTION OF NEW STELLAR SOURCES OF VIBRATIONALLY EXCITED SILICON MONOXIDE MASER EMISSION AT 6.95 MILLIMETERS

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ABSTRACT

We have searched 32 selected sources for $v = 1$, $J = 1 \rightarrow 0$ SiO maser emission at 43,122.0 MHz ($\sim$6.95 mm), and detected 16 of them. Two of them, Ori A and W Hya, had been detected previously by Thaddeus *et al.* We detected eight of the SiO $v = 1$, $J = 2 \rightarrow 1$ SiO maser sources observed by Kaifu, Buhl, and Snyder at 86,243.27 MHz ($\sim$3.48 mm), and found that the $v = 1$, $J = 1 \rightarrow 0$ maser is often the most intense transition, and hence promises to be the best frequency to use in searching for new maser sources. Most of the detected maser sources reported in this paper can readily be associated with known late-type stars; therefore we have been able to analyze the velocity patterns and stellar classification implications found from our data. The proposed maser mechanisms are discussed in the context of current observations.

Subject headings: late-type stars — masers — molecules, interstellar

I. INTRODUCTION

In 1973 December, a group of molecular emission lines near 3.4 mm wavelength was detected from the direction of the Orion molecular cloud, and tentatively identified as maser emission from the $J = 2 \rightarrow 1$ transition of silicon monoxide (^{28}SiO) in its first vibrationally excited state ($v = 1$) at 86,243.27 MHz rest frequency (Snyder and Buhl 1974). Subsequently, a series of significant observations yielded detections which confirmed the identification of vibrationally excited SiO beyond doubt: $v = 1$, $J = 3 \rightarrow 2$ at 129,363.1 MHz from Ori A (Davis *et al.* 1974); $v = 1$, $J = 1 \rightarrow 0$ at 43,122.00 MHz from W Hya and Ori A (Thaddeus *et al.* 1974); and $v = 2$, $J = 1 \rightarrow 0$ at 42,820.51 MHz from *o* Cet, Ori A, VY CMa, R Leo, and W Hya (Buhl *et al.* 1974). While the molecular identification was still being confirmed, a survey of the SiO $v = 1$, $J = 2 \rightarrow 1$ transition demonstrated that many of the emission sources are stars, either Mira or semiregular variables, which also display OH/H_2O maser emission, and a rough correlation was demonstrated between the existence of SiO maser emission and the measured infrared flux. No SiO maser emission was detected from OH/H_2O/IR sources in H II regions.

In this paper, we report the results of a search of 32 sources for maser emission from the SiO $v = 1$, $J = 1 \rightarrow 0$ transition; 16 of these produced positive detections. All of the 12 sources of SiO $v = 1$, $J = 2 \rightarrow 1$ emission reported by Kaifu, Buhl, and Snyder (1975) were observed, and eight were detected.

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Several interesting implications of our observational results are discussed.

II. OBSERVATIONS

The observations were made during 1974 June with the 36-foot (11 m) telescope of the National Radio Astronomy Observatory. The half-power beamwidth was $\sim$160″. The NRAO 31–50 GHz mixer receiver (1500 K SSB system temperature) and 256-channel filter bank with 100 kHz filter separation (0.695 km s^{-1}) were used. A chopping wheel in front of the feed was used for temperature calibration. The antenna temperature of a spectral line measured by this calibration method, T_A*, is related to the true antenna temperature, T_A, by

$$T_A{}^* = T_A \frac{e^{\tau \sec z}}{\eta_l}$$

where $e^{\tau \sec z}$ is the atmospheric loss factor, and the antenna loss efficiency, η_l, is the correction for antenna ohmic loss, blockage by support spars and radiometer, and forward beam coupling efficiency (Ulich 1974). Due to solar heating of the antenna, it was necessary to observe several sources through the fabric telescope dome which attenuates the signal by $\sim$40 percent; thus for these sources the displayed temperature scales have been increased by 1.67 to offset the dome attenuation.

The spectra of the 16 detected SiO $v = 1$, $J = 1 \rightarrow 0$ maser sources at 43,122.0 MHz are plotted in figures 1–3. Two of these sources, Ori A and W Hya, were initially detected by Thaddeus *et al.* (1974) with the 16-ft (5 m) antenna of the Texas Millimeter Wave Observatory. In addition, following our observations,

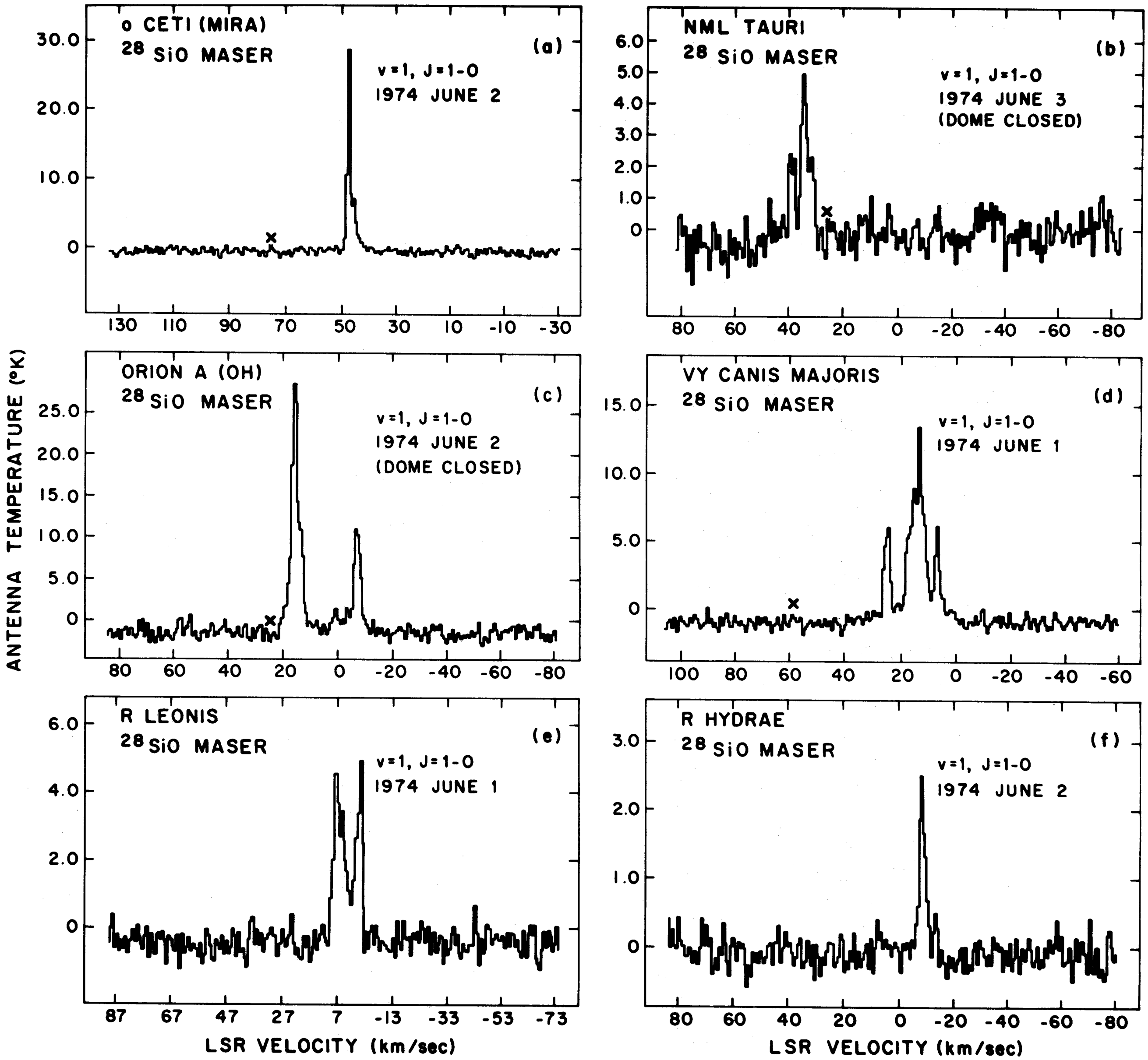

FIG. 1.—SiO $v = 1, J = 1 \rightarrow 0$ emission spectra for (*a*) o Cet, (*b*) NML Tau, (*c*) Ori A, (*d*) VY CMa, (*e*) R Leo, and (*f*) R Hya. *Ordinates*, antenna temperature $T_A{}^*$; *abscissae*, radial velocity with respect to the LSR calculated for a rest frequency of 43,122.0 MHz. To convert the given LSR velocities to heliocentric velocities (in km s^{-1}), add 10.2 to (*a*); 12.3 to (*b*); 18.0 to (*c*); 19.0 to (*d*); 7.5 to (*e*); and −1.9 to (*f*).

we learned that o Cet, R Cas, and several other sources had been independently detected by Spencer, Schwartz, and Mather (1975) with the 85-foot (26 m) antenna of the Naval Research Laboratory.

Several interesting properties of the SiO $v = 1$, $J = 1 \rightarrow 0$ maser sources are listed in table 1. The first column gives the source name and, when available, the IRC number from Neugebauer and Leighton (1969). The second column gives epoch 1950 source coordinates with the telescope pointing error $(\Delta\alpha, \Delta\delta)$ $[\equiv(\alpha, \delta)_{\text{source}} - (\alpha, \delta)_{\text{telescope}}]$ following in parentheses; the pointing errors occurred because of discrepancies between source positions reported in the literature. Hence, to standardize our pointing, epoch 1950 coordinates from Kukarkin *et al.* (1972) have been listed for stellar sources in column (2) except when more relevant positions (such as OH interferometer measurements) are available. The peak velocity (with respect to the local standard of rest) and emission range for each SiO $v = 1, J = 1 \rightarrow 0$ maser emission line are given in column (3); these velocities are based on a rest frequency of 43,122.00(10) MHz from Lovas (1974). Column (4) lists the peak antenna temperature, $T_A{}^*$, for each resolved emission feature

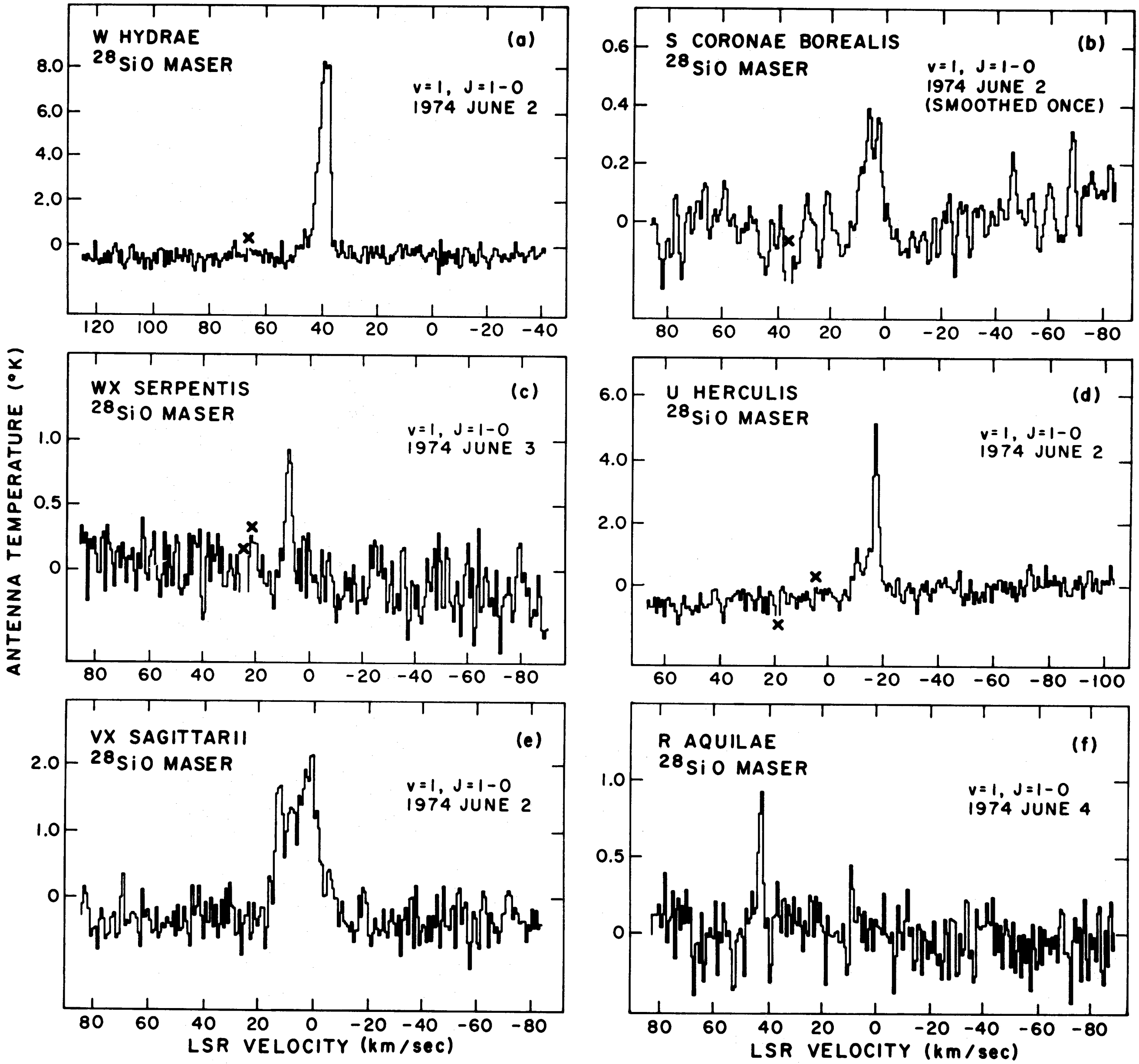

FIG. 2.—SiO $v = 1$, $J = 1 \rightarrow 0$ emission spectra for (*a*) W Hya, (*b*) S CrB, (*c*) WX Ser, (*d*) U Her, (*e*) VX Sgr, and (*f*) R Aql. *Ordinates*, antenna temperature $T_A{}^*$; *abscissae*, radial velocity with respect to the LSR calculated for a rest frequency of 43,122.0 MHz. To convert the given LSR velocities to heliocentric velocities (in km s^{-1}), add -2.0 to (*a*); -16.4 to (*b*); -16.0 to (*c*); -18.1 to (*d*); -12.2 to (*e*); and -18.0 to (*f*).

in figures 1–3. The peak flux measurements, column (5), were determined from

$$F_\nu = \frac{2k}{\eta_A A}\,\eta_l T_A{}^* = 44.4068\ T_A{}^*\ \mathrm{Jy}\,,$$

where the antenna loss efficiency, η_l, is 0.73; the aperture efficiency, η_A, is 0.35; the geometric area of the antenna, A, is 94.5637 m^2; and 1 Jy $= 10^{-26}$ W m^{-2} Hz^{-1}. The value of η_A can change by 15 percent with ambient temperature (Ulich 1974). Columns (6) and (7) list spectral type and variable type from Kukarkin *et al.* (1969), unless otherwise noted. Column (8) lists the velocities at peak emission for the $v = 1$, $J = 2 \rightarrow 1$ SiO maser (with rest frequency 86,253.27 MHz) surveyed by Kaifu *et al.* (1975). Columns (9), (10), and (11) give H_2O and OH velocities at peak emission; no OH 1720 MHz emission is listed because only one stellar source, V1057 Cyg, is known (Lo and Bechis 1974). In column (8), ns means that the source was not surveyed by Kaifu *et al.* (1975). In columns (9), (10), and (11), nd means that the source was searched but

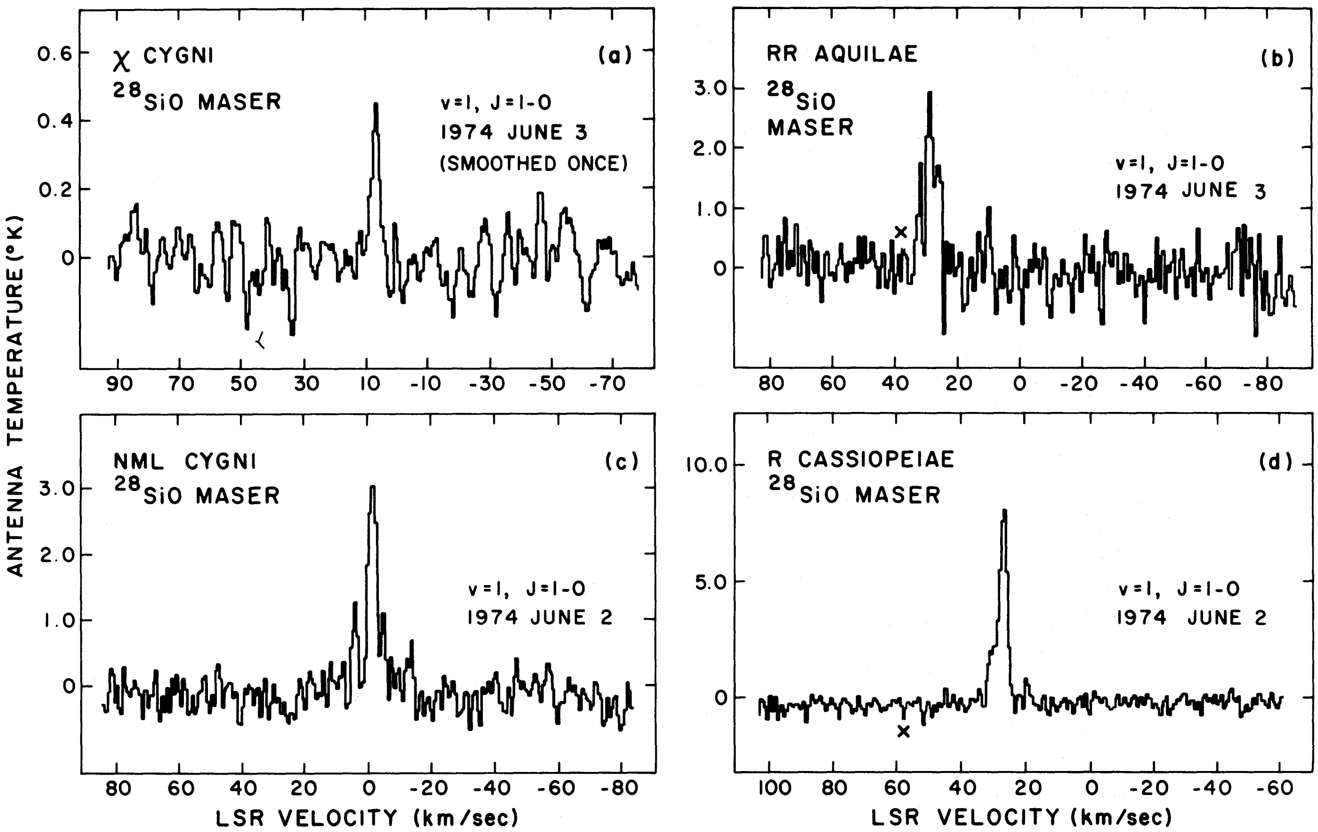

FIG. 3.—SiO $v = 1, J = 1 \rightarrow 0$ emission spectra for (*a*) χ Cyg, (*b*) RR Aql, (*c*) NML Cyg, and (*d*) R Cas. *Ordinates*, antenna temperature T_A^*; *abscissae*, radial velocity with respect to the LSR calculated for a rest frequency of 43,122.0 MHz. To convert the given LSR velocities to heliocentric velocities (in km s^{-1}), add -18.4 to (*a*); -14.9 to (*b*); -16.5 to (*c*); and -8.1 to (*d*).

H_2O or OH was not detected. Column (12) gives the source distance when known; except when otherwise noted, parallactic distances from Becvar (1964) are listed. Parentheses are placed around distances derived from luminosity relationships. The negative results are given in table 2, which is similar to table 1 except that the velocity search range is in column (3) and upper limits to antenna temperature, T_A^*, and flux, F_ν, are in columns (4) and (5), respectively. From column (8) it should be noted that four of the sources for which we found negative results for the SiO $v = 1$, $J = 1 \rightarrow 0$ transition are sources of maser emission for the $v = 1, J = 2 \rightarrow 1$ transition at 86,243.27 MHz; these are S Per, IRC+50137, U Ori, and RX Boo. In columns (9), (10), and (11), nr means that negative results may have been obtained for H_2O or OH, but not reported in the literature. During this work, Herbig (1974) pointed out that coordinate errors in the literature may obscure the fact that CIT 6 (see table 2) is identical with RW LMi. Hence our negative result for CIT 6 is also a negative result for RW LMi.

III. DISCUSSION

a) SiO $v = 1, J = 1 \rightarrow 0$ *and* $J = 2 \rightarrow 1$ *Photon Flux Comparisons*

The low intensity of the Ori A SiO $v = 1, J = 3 \rightarrow 2$ transition at 129,363.1 MHz prompted Davis *et al.* (1974) to suggest that the $v = 1, J = 1 \rightarrow 0$ transition at 43,122.00 MHz might be the most intense of all. The subsequent detection of the latter transition in W Hya and Ori A by Thaddeus *et al.* (1974) implied that these two sources are saturated masers, and gave impetus to the idea that, for many sources, the $v = 1$, $J = 1 \rightarrow 0$ transition may be the best search frequency for SiO maser emission. To investigate whether this transition is the most intense, we searched the 13 sources of $v = 1$, $J = 2 \rightarrow 1$ SiO emission at 86,243.27 MHz reported earlier, as well as several sources which produced negative results (Kaifu *et al.* 1975; Snyder and Buhl 1974). From columns (4) and (8) of tables 1 and 2, it may be seen that nine of the $v = 1$, $J = 2 \rightarrow 1$ SiO maser sources were also detected in the $v = 1$, $J = 1 \rightarrow 0$ transition, but four were not (S Per, IRC+50137, U Ori, and RX Boo). Three sources were found to have $v = 1, J = 1 \rightarrow 0$ emission, which produced negative results for $v = 1$, $J = 2 \rightarrow 1$ (S CrB, WX Ser, and R Aql). In order to compare the two search frequencies, the integrated photon flux, $F_\nu \Delta\nu(h\nu)^{-1}$ photons cm^{-2} s^{-1}, has been summed over all velocity components for each source at each of the two frequencies; the results are plotted in figure 4. Unresolved and blended spectral lines probably are a greater source of uncertainty for the integrated photon flux points in figure 4 than the possibility of severe flux changes due to SiO time

TABLE 1

MASER SOURCES OF ^{28}SiO $v = 1$, $J = 1$–0 EMISSION AT 43.122 GHz

SOURCE (1)	α(1950), (Δα) δ(1950), (Δδ) (2)	V_{LSR} (km s^{-1}) (3)	T_A*(K) (4)	F_ν (Jy) (5)	SPECTRAL TYPE (6)	VARIABLE TYPE (7)	SiO EMISSION, 86.243 GHz V_{LSR}(km s^{-1}) (8)	H_2O EMISSION, 22.235 GHz V_{LSR}(km s^{-1}) (9)	OH EMISSION 1612 MHz V_{LSR}(km s^{-1}) (10)	OH EMISSION 1665, 7 MHz V_{LSR}(km s^{-1}) (11)	d (pc) (12)
o Cet (Mira) (IRC+0030).....	$2^h16^m49^s$,(0^s) $-3°12'\ 12''$,$(0'')$	+46(44 → 48)	30	1332	M5e–M9e	M	ns	+47[1]	nd[2,3,4]	+47[1]	250
NML Tau[5] (IRC+10050)....	3 50 46,(0) +11 15 42,(0)	+35(31 → 36) +39(38 → 41)	5.3 2.8	235 124	M8e[6]	M[6]	ns	+18.7 → 28[7]	+17.4[2,3] +50.4	+15[2,3]	(270)[8]
Ori A(OH)[9] (Becklin's star)...	5 32 46.9,(−0.1) − 5 24 18,(3)	− 7(−9 → −5) +16(12 → 20)	12 29	533 1288	?	?	−7(−9 → −5) +17(13 → 19)	−6(−8 → −4)[10] +15(13 → 18)	+13 → 18[11]	− 8 → −5[11] +14 → 24	500
VY CMa[12] (IRC−30087)....	7 20 55.0,(0) −25 40 11,(0)	+ 5(4 → 6) +12(9 → 18) +23(22 → 26)	7 14 7	311 622 311	M5e Ib pec	Lc	+11(−3 → 18) +30(26 → 37)	+14.5[10] +18 +35	−11 → −3[13] +38 → 55	+1 → 9[13]	(400)[8] or 1500[14]
R Leo (IRC+10215)....	9 44 52,(0) +11 39 42,(1)	− 2(−3 → 1) + 7(3 → 8)	5.5 5.1	244 226	M6.5e–M9e	M	+7	−1[1]	nd[3,4,15]	+3.2[15]	1000
R Hya..........	13 26 59,(1) −23 01 30,(−6)	− 9(−11 → −7)	2.7	120	M6e–M8e	M	ns	nd[1]	nd[3]	nd[3,16]	...
W Hya[17] (IRC−30207)....	13 46 12.2,(0.2) −28 07 03,(3)	+38(35 → 42)	8.6	382	M8e–M9e	SR*a*	+39(36 → 41) +44	+42[18]	nd[4]	+38[4,19] +46	(100)[19]
S CrB[17] (IRC+30272)....	15 19 21.4,(0.4) +31 32 45,(−3)	+ 5(−1 → 10)	0.4	18	M6e–M8e	M	nd	+1[18]	−2[4]	−2[17] +4	(375)[19]
WX Ser (IRC+20281)....	15 25 32,(0) +19 44 24,(18)	+ 7(5 → 9)	0.9	40	M8e	M	nd	nd[7]	− 0.5[2,3] +13.2	−0.5[2,3]	(970)[8]
U Her[17] (IRC+20298)....	16 23 34.6,(−0.4) +19 00 18,(1)	−16(−18 → −13) −10(−11 → −9)	5.4 1.6	240 71	M6.5e–M8e	M	−16 −10	−15[18]	nd[4]	20[4,19] −14 → −10	200 or (325)[19]
VX Sgr[20] (IRC−20431)....	18 05 03.2,(0.2) −22 14 06,(6)	− 1(−3 → 14)	2.4	106	M4e	SR*b*	−2 +5	+3[18] +14	−17 → −2[21,22] +11 → 29	0 → 5[22,23] +10 → 16	(500)[8]
R Aql[20] (IRC+10406)....	19 03 57.7,(0.3) + 8 09 11,(0)	42(41 → 44)	0.9	40	M5e–M8e	M	nd	+47 → 49[18]	+40 → 45[2,3] +53.8(52 → 55)	+40 → 45[2,3] +51 → 54	(300)[8]
χ Cyg (IRC+30395)....	19 48 38,(−1) +32 47 12,(0)	+ 9(7 → 11)	0.4	18	S7,1e–S10,1e	M	+9	nd[1]	nd[2,3]	nd[3]	71
RR Aql (IRC+00458)....	19 55 01,(3) − 2 01 12,(0)	+30(25 → 31) +32(32 → 35)	3 1.8	133 80	M6e–M7e	M	ns	27.9(25 → 30)[7]	+20 → 25[3] +30 → 35	+22 → 27[3]	(400)[8]
NML Cyg[24] (IRC+40448)....	20 44 33.8,(−0.2) +39 55 56,(3)	−12(−14 → −10) 0(−4 → 2) + 4(3 → 6)	1.0 3.3 1.6	44 146 71	M7[25]	?[6]	−10 + 1(−2 → 7)	−19[18]	−30 → −5[2] + 4 → 25	−20 → −19[2,26]	(500)[8]
R Cas (IRC+50484)....	23 55 52,(−1) +51 06 36,(0)	+28(26 → 33)	8.4	373	M6e–M8e	M	+23	26.1[7]	nd[4,19,22]	+21[4,19] +28 → 31	(195)[19]

REFERENCES.—[1] Dickinson 1974; Schwartz 1974. [2] Wilson, Barrett, and Moran 1970. [3] Wilson and Barrett 1972. [4] Rieu, Fillet, and Gheudin 1971. [5] Neugebauer, Martz, and Leighton, 1965; Neugebauer and Leighton 1969. [6] Wing, Spinrad, and Kuhi 1967. [7] Dickinson, Bechis, and Barrett 1973. [8] Luminosity distance from Hyland *et al.* 1972. [9] 1665 MHz OH interferometer position in LSR velocity range 17.6–23.7 km s^{-1} (Raimond and Eliasson 1969). [10] Sullivan 1973; other H_2O features also present. [11] Weaver, Dieter, and Williams 1968; other OH features also present. [12] OH interferometer position (Eliasson and Bartlett 1969). [13] Robinson, Caswell, and Goss 1970. [14] Herbig 1969. [15] Fillet, Foy, and Gheudin 1973. [16] Fillet *et al.* 1972. [17] OH interferometer position (Hardebeck and Wilson 1971). [18] Schwartz, Harvey, and Barrett 1974; Schwartz and Barrett 1970. [19] Wilson *et al.* 1972. [20] OH interferometer position (Hardebeck 1972). [21] Caswell and Robinson 1970. [22] Paschenko *et al.* 1971. [23] Robinson, Caswell, and Dickel 1971. [24] OH interferometer position (Wilson, Barrett, and Moran 1970). [25] Johnson 1968. [26] Wilson and Barrett 1968.

TABLE 2

NEGATIVE RESULTS FOR THE ^{28}SiO $v = 1, J = 1\text{–}0$ MASER

SOURCE (1)	α(1950), (Δα) δ(1950), (Δδ) (2)	V_{LSR} SEARCH RANGE (km s^{-1}) (3)	PEAK-TO-PEAK NOISE (K) (4)	F_ν UPPER LIMITS (Jy) (5)	SPECTRAL TYPE (6)	VARIABLE TYPE (7)	SiO EMISSION 86.243 GHz V_{LSR}(km s^{-1}) (8)	H_2O EMISSION 22.235 GHz V_{LSR}(km s^{-1}) (9)	OH EMISSION: 1612 MHz V_{LSR}(km s^{-1}) (10)	OH EMISSION: 1665, 7 MHz V_{LSR}(km s^{-1}) (11)	d (pc) (12)
S Per (IRC+60088)....	2ʰ19ᵐ16ˢ,(0ˢ) +58°21′ 36″,(6″)	−100 → 60	0.8	36	M3e Ia–M4e Ia	SR*c*	−34	−47[1] −38[1,2]	−24[3] −53	nd[3]	...
T Tau	4 19 04,(−3) +19 25 06,(−6)	− 80 → 130	3.3	146	dG5e(T)	InT	ns	nr	nd[4,5]	nd[4,5]	...
R Tau (IRC+10060)....	4 25 33,(−3) +10 03 12,(18)	− 80 → 80	2.5	111	M5e–M7e	M	ns	12[2]	nr	nd[6]	...
IRC+50137[7]	5 07 20.1,(0.1) +52 48 48,(−6)	− 80 → 80	0.8	36	...	...	+1	nd[8]	−14[4,5] +20	19[4]	(820)[9] or 1800[5]
α Ori (IRC+10100)....	5 52 28,(0) + 7 23 54,(−6)	− 80 → 80	1.7	75	M2 Iab	SR*c*	ns	nd[8]	nd[4,5]	nd[4]	143
U Ori[10] (IRC+20127)....	5 52 50.9,(−0.1) +20 10 14,(8)	−120 → 40	2.0	89	M6e–M8e	M	−42 −40	−36.8[8,11,12]	nd[12,13]	−41.8[12] −35.8	(280)[12]
CIT 6[14] (IRC+30219)....	10 13 12,(0) +30 49 24,(0)	− 80 → 80	0.6	27	...	...	nd	nr	nd[4,5]	nd[4,5]	...
V Ant	10 18 55,(−0.3) −34 32 48,(15)	− 80 → 80	1.7	75	M7 IIIe	M	ns	−18[2]	nr	nr	...
U CVn (IRC+40238)....	12 44 56,(−1) +38 38 54,(31)	− 80 → 80	0.7	31	M7e	M	nd	−22[2]	nr	nr	...
RT Vir (IRC+10262)....	13 00 06,(1) + 5 27 12,(6)	− 80 → 80	0.4	18	M8	SR*b*	nd	16[2]	nd[4]	nd[4]	...
RX Boo (IRC+30257)....	14 21 57,(−1) +25 55 48,(−5)	− 80 → 80	0.8	36	M7e–M8e	SR*b*	0 +4	5[8,11]	nd[4,15]	nd[4,15]	...
α Sco (Antares) (IRC−30265)....	16 26 20,(0) −26 19 24,(0)	− 80 → 80	1.1	49	M1 Ib	SR*a*	ns	nr	nd[4,5,16]	nd[5]	111
OH 1649−41[7] ...	16 49 52.2,(0.2) −41 43 47,(1)	− 80 → 80	0.8	36	...	...	ns	nd[17]	−30 → −19[4] −65 → −52	nd[4]	...
UX Cyg (IRC+30464)....	20 53 00,(0) +30 13 24,(0)	− 80 → 80	0.5	22	M4e–M6e	M	nd	nd[8]	−14 → −4[4]	nd[4]	(900)[9]
V Mic	21 20 38,(1) −40 54 54,(18)	− 80 → 80	0.9	40	M6e	M	ns	nr	−6 → −2[16] +5 → 10	+4 → 8[16]	...
TW Peg (IRC+30481)....	22 01 43,(2) +28 06 18,(−12)	− 80 → 80	1.0	44	M6–M7	SR	nd	−7[2]	nr	nr	...

REFERENCES.—[1] Baudry and Welch 1974. [2] Dickinson 1974; Schwartz 1974. [3] Dickinson, Kollberg, and Yngvesson 1974. [4] Wilson and Barrett 1972. [5] Wilson, Barrett, and Moran 1970. [6] Fillet *et al.* 1972. [7] OH interferometer position (Hardebeck 1972). [8] Dickinson, Bechis, and Barrett 1973. [9] Luminosity distance from Hyland *et al.* 1972. [10] OH interferometer position (Hardebeck and Wilson 1971). [11] Schwartz, Harvey, and Barrett 1974. [12] Wilson *et al.* 1972. [13] Paschenko *et al.* 1971. [14] Ulrich *et al.* 1966; Neugebauer and Leighton 1969. [15] Wilson and Riegel 1973. [16] Caswell, Robinson, and Dickel 1971. [17] Johnson, Sloanaker, and Bologna 1973.

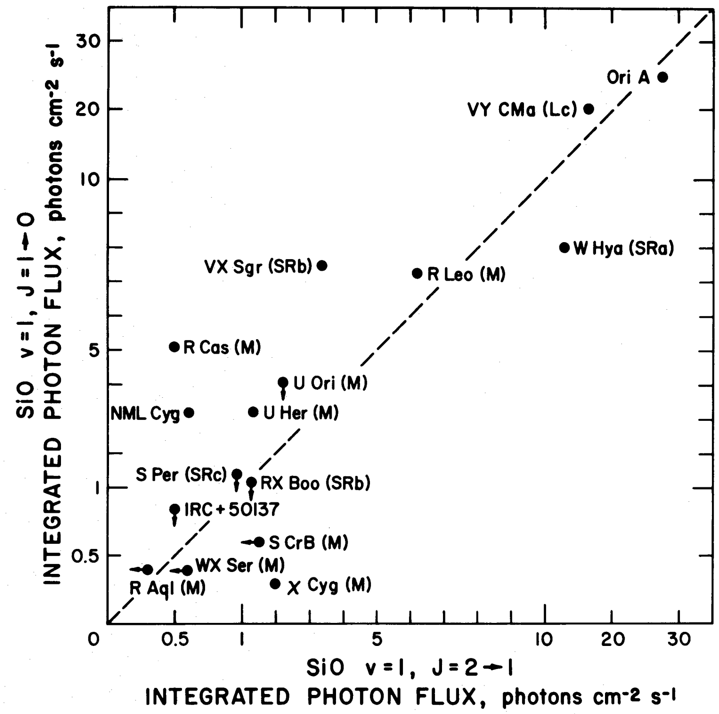

FIG. 4.—Comparison of the total integrated photon flux, $F_\nu \Delta\nu (h\nu)^{-1}$ for the SiO $v = 1, J = 2 \rightarrow 1$ and $1 \rightarrow 0$ transitions. Sources with arrows pointing down, e.g., U Ori, have only upper limits detected for the $v = 1, J = 1 \rightarrow 0$ transition; sources with arrows pointing left, e.g., R Aql, have only upper limits detected for the $v = 1, J = 2 \rightarrow 1$ transition. The dashed line along the diagonal marks the position of equal photon flux from both transitions. Most sources have more photon flux in the $v = 1, J = 1 \rightarrow 0$ transition and hence are above the dashed line.

variation. If the seven sources in figure 4 with only upper limits at either 43,122.00 or 86,243.27 MHz are ignored, it is striking that seven of nine sources have either equal or more photon flux in the $v = 1$, $J = 1 \rightarrow 0$ than in the $v = 1, J = 2 \rightarrow 1$ transition. Hence, given the limited amount now known about sources of vibrationally excited SiO, we conclude that the $v = 1$, $J = 1 \rightarrow 0$ transition is the best search frequency for many sources. It is also interesting that several sources (in particular R Cas and NML Cyg) have more microwave quanta emitted from the $v = 1$, $J = 1$ level than from the $v = 1$, $J = 2$ level; both this excess photon flux in the $v = 1, J = 1 \rightarrow 0$ transition and the detection of the SiO $v = 2, J = 1 \rightarrow 0$ (Buhl *et al.* 1974) transition show that the SiO maser pumping mechanism involves vibrational energy levels higher than $v = 1$.

It may be seen from figure 4 that for S Per, RX Boo, and R Aql, the photon flux limits reached for the SiO $v = 1$, $J = 1 \rightarrow 0$ transition were approximately equal to the limits reached by Kaifu *et al.* (1975) for the $v = 1$, $J = 2 \rightarrow 1$ transition. Weak emission at 86,243.27 MHz was detected from both S Per and RX Boo in 1974 March, but 3 months later we could not find 43,122.0 MHz emission from either source (see table 2). Conversely, we detected a weak 43,122.0 MHz emission line from R Aql (see fig. 2), whereas 3 months earlier Kaifu *et al.* (1975) found a negative result at 86,243.27 MHz. Hence, if all SiO sources have the same type of maser mechanism, this may be the first observational hint of time variation in the SiO maser. However, we emphasize that all three sources are so weak that they should be observed again at both frequencies, preferably at the same time, before any definite conclusions can be drawn about time variations.

b) *Suggested Observational Correlations*

It may be seen from tables 1 and 2 that all of the classified stellar SiO maser sources except χ Cyg are M4 to M8 spectral type; furthermore, all of these are Mira (M), irregular (Lc), or semiregular (SR*a*, SR*b*) variables. When the observational statistics become more complete and the bias of selection is reduced, the SiO maser might be useful for stellar detection in dusty, obscured regions, and for rough classification of spectral and variable type. For example, Becklin's infrared star (Becklin and Neugebauer 1967) may be responsible for the Ori A SiO maser emission.[1] Whether it is or not probably will be determined by future millimeter-wave interferometry, but in the meantime it appears to be very possible that the Ori A SiO maser is due to an M, SR, or Lc pulsating variable star of M spectral type (see the discussions by

[1] Kukarkin *et al.* (1972) list a star of suspected variability, number 100578, with epoch 1950 coordinates $\alpha = 5^h32^m47^s$, $\delta = -5°24'.5$. Thus 100578 is well within the beamwidth for Ori A (OH) and Becklin's star, but it is not an M-type star (Herbig 1974), and hence probably not the SiO maser source.

Becklin and Neugebauer [1967] and Penston, Allen, and Hyland [1971]). In addition, part of the Ori A H_2O maser emission pattern originates from the Ori A SiO maser source (Snyder and Buhl 1974).

All but four of the 20 SiO maser sources in tables 1 and 2 are known sources of microwave H_2O maser emission, and it is possible that the four H_2O nondetections were due to a minimum in the H_2O time variation cycle (see, e.g., Schwartz, Harvey, and Barrett 1974). Hence, based on our limited data, there is at least an 80 percent chance that a source of SiO maser emission is also a microwave H_2O maser source. Also, about 75 percent of the 21 stellar H_2O masers surveyed were found to be SiO maser sources. The statistics for OH emission are very similar: 75 percent of the 20 SiO maser sources are 1612 or 1665/1667 MHz OH maser sources, and about 83 percent of the 18 stellar OH sources surveyed are SiO maser sources. As with H_2O, it is possible that some of the SiO maser sources have not been detected in OH because of time-varying intensities (see, e.g., Harvey *et al.* 1974). The failure to detect SiO emission from several OH/H_2O sources listed in table 2 may be because either the SiO maser intensities vary with time and our observations coincided with a minimum in the intensity, or because the group of stars with detectable SiO emission heavily overlaps the group of OH/H_2O stellar masers but does not include all of them. The latter possibility would also be consistent with the negative OH and H_2O results reported for χ Cyg and R Hya (see references cited in table 1). Hence, we conclude that WX Ser and IRC+50137 should be monitored carefully for microwave H_2O emission; *o* Cet and S Per for OH emission; and R Hya and χ Cyg for both OH and H_2O emission.

We have attempted to correlate source distance (col. [12], table 1) with either peak flux (col. [5], table 1) or integrated photon flux, but no obvious relationship has emerged from our data. It is interesting to note, however, that all of the sources with tabulated distances in table 1 are at a distance of only 1 kpc or less, with the possible exception of VY CMa (Herbig 1969). This suggests that the failure to detect SiO emission from known OH/H_2O/IR sources in several H II regions (Snyder and Buhl 1974; Kaifu *et al.* 1975) could be due to the beam dilution which results from observing sources which are significantly more distant than 1 kpc.

c) SiO *Velocities*

Extensive radio observations comparing stellar H_2O and OH microwave emission-line velocities to those of optical absorption and emission lines (Wilson, Barrett, and Moran 1970; Wilson and Barrett 1972; Wilson *et al.* 1972; Dickinson, Bechis, and Barrett 1973) have led to the conclusions that (i) the higher OH velocity usually is associated with the stellar velocity; i.e., this OH cloud is approximately stationary with respect to the star; (ii) the lower velocity OH is moving outward from the star on the near side (toward the solar system), and the observed emission is caused by radiation from the central exciting star; (iii) the H_2O velocity falls between the higher and lower OH velocity components. Thus the H_2O cloud is expanding outward between the higher velocity OH cloud around the star and the lower velocity OH cloud which is moving outward more rapidly at the extreme boundary of the emission region.

Table 1 lists vibrationally excited SiO detections in the following types of OH/IR stars (see Wilson 1973 for a catalog of OH/IR stars and a summary of the classification method):

Type I (1665/1667 MHz OH + H_2O).—R Leo, W Hya, S CrB, U Her, and R Cas.

Type II (strong 1612 MHz OH).—NML Tau, WX Ser, R Aql, and RR Aql.

Supergiants (strong 1612 MHz OH + H_2O).—VY CMa, VX Sgr, and NML Cyg.

In all three types of OH/IR star, the $v = 1$, $J = 1 \rightarrow 0$ SiO emission velocities fall between the lower OH velocity (or, as for R Leo, the optical emission velocity) and the higher OH (or stellar) velocity. Thus the observed SiO cloud is between the star and the outer boundary of the OH emission region, moving outward toward the solar system at a lower velocity than the extreme OH cloud. Furthermore, for the Type I sources R Leo, S CrB, U Her, and R Cas; Type II sources NML Tau and RR Aql; and the supergiant NML Cyg, the $v = 1$, $J = 1 \rightarrow 0$ SiO emission velocity distribution tends to be between the H_2O velocity and the stellar velocity. Hence, for these sources, the SiO cloud typically moves outward from the star at a *lower* velocity than H_2O. Following the cloud geometries discussed by Wallerstein (1971, 1973), this suggests that the excitation region for the SiO cloud starts very near the star (which would be allowed for SiO because of its high dissociation energy of ~ 8 eV or 9.28×10^4 K), and extends through the chromosphere and well into the cooler envelope which supports the H_2O maser emission. On the other hand, RR Aql and the supergiant VX Sgr have more complex velocity patterns, with SiO velocity components located between H_2O velocity components and the lower OH velocity. For the supergiant VY CMa, Moran *et al.* (1973) found that the 35 km s^{-1} H_2O velocity feature listed in table 1 disappeared after 1970 June; the remaining 14.5 and 18 km s^{-1} H_2O features are spatially separated by $\sim 0\overset{''}{.}10$. Without the 35 km s^{-1} H_2O feature, the SiO velocities cluster around the 14.5 and 18 km s^{-1} H_2O features, and the overall VY CMa OH/H_2O/SiO velocity pattern weakly resembles that found for W Hya, but on a larger scale. These sources may have to be explained through an extension of the tilted-disk model proposed by Herbig (1972) for VY CMa, but interferometric measurements of SiO maser sources will have to be made before any definitive model for the SiO velocity patterns can be adopted.

d) *The Proposed Maser Mechanisms*

A résumé of the observations thus far which possibly will be relevant for explaining the SiO maser mechanism includes the following.

i) *Intensities*

The SiO $v = 1, J = 3 \rightarrow 2$ emission, detected only from Ori A by Davis *et al.* (1974), has been found to be considerably weaker than the $v = 1, J = 2 \rightarrow 1$; $v = 1, J = 1 \rightarrow 0$; or $v = 2, J = 1 \rightarrow 0$ maser emission from Ori A (Snyder and Buhl 1974; Thaddeus *et al.* 1974; Buhl *et al.* 1974). For each source compared in this paper, the intensity of the $v = 1, J = 1 \rightarrow 0$ transition is greater than or equal to that found for the $v = 1, J = 2 \rightarrow 1$ transition, except for χ Cyg, VY CMa, and W Hya (see fig. 4). Interestingly enough, for the latter two sources Buhl *et al.* (1974) found that the $v = 2, J = 1 \rightarrow 0$ transition is about as intense as the $v = 1, J = 1 \rightarrow 0$ transition. To summarize briefly, for the majority of sources surveyed so far, the first vibrationally excited state typically has the intensity hierarchy $J = 1 \rightarrow 0 > 2 \rightarrow 1 > 3 \rightarrow 2$, with the $J = 3 \rightarrow 2$ possibly not detectable. For two sources, VY CMa and W Hya, the intensity ordering has $J = 2 \rightarrow 1 \geq J = 1 \rightarrow 0$ in the first vibrationally excited state, and the $J = 1 \rightarrow 0$ transition has about the same intensity in both the first and second vibrationally excited states.

ii) *Correlations*

As discussed previously, there is a high correlation between SiO stellar maser sources and OH/H_2O stellar maser sources, with a tendency for the SiO velocities to range between the H_2O and stellar velocities.

iii) *Line Shapes*

The $v = 1, J = 1 \rightarrow 0$ spectra have more narrow, unresolved features than the $v = 1, J = 2 \rightarrow 1$ spectra. All sources shown in figures 1, 2, and 3 have one or more spectral components which are not resolved at 100 kHz (0.695 km s^{-1}) resolution.

iv) *Maser versus Infrared Sources*

Several sources of SiO maser emission, e.g., VY CMa, RX Boo, and χ Cyg, are also known infrared SiO sources (Gillett, Stein, and Solomon 1970; Wollman *et al.* 1973); but several infrared SiO sources, e.g., α Ori, α Sco, and α Her, have given negative results for the SiO maser (see table 2, this paper; Kaifu *et al.* 1975; Cudaback, Gaustad, and Knacke 1971; Wollman *et al.* 1973). For the latter sources, this result suggests either that the negative SiO maser observations were made at the wrong phase, if time variations are significant, or that a relatively high abundance of SiO in the atmosphere of a giant or supergiant is not enough in itself to guarantee the existence of an SiO maser.

v) *Negative Results*

Thus far only negative results have been found in the search for an SiO $v = 0, J = 1 \rightarrow 0$ maser (Buhl *et al.* 1974), and for an SiO $v = 2, J = 2 \rightarrow 1$ maser (Snyder, Kaifu, and Buhl 1975). Also, Davis *et al.* (1974) have searched unsuccessfully for maser emission from the $v = 1, J = 1 \rightarrow 0$ transition of CO.

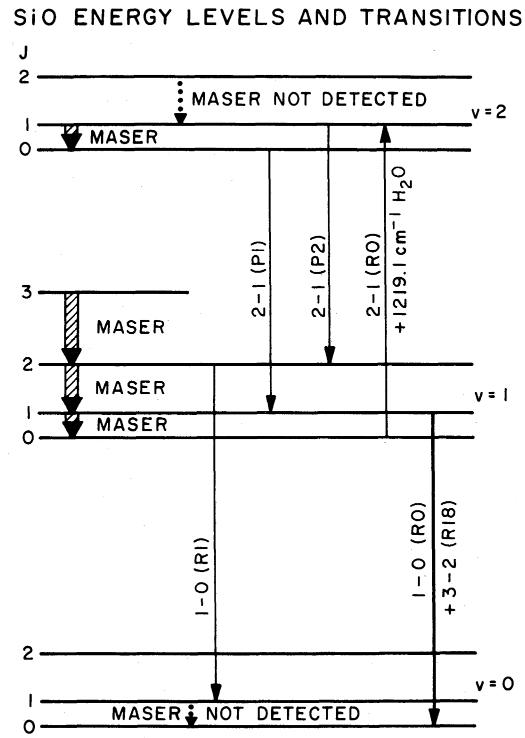

FIG. 5.—Schematic diagram showing SiO energy levels (not drawn to scale) and transitions likely to be important for explaining the maser mechanism. Broad, shaded arrows show the detected SiO maser transitions, dotted arrows show those not detected, and the thin, solid arrows show infrared transitions.

Geballe and Townes (1974) have proposed several possible mechanisms for SiO maser emission. It appears that one variation of their resonance infrared line pumping scheme would give a qualitative explanation of the observational results. If an infrared transition of H_2O at 1219.1 cm^{-1} produces excess radiation, its close coincidence with the SiO $v = 2 \rightarrow 1$ (R0) line would depopulate the SiO $v = 1, J = 0$ level and overpopulate the SiO $v = 2, J = 1$ level (see fig. 5). Excess photons would leave the $J = 1$ level, cascading down and branching as follows: (1) $v = 2, J = 1 \rightarrow 0$, causing the SiO maser detected by Buhl *et al.* (1974), and then through $v = 2 \rightarrow 1$ (*P*1) to overpopulate the $v = 1, J = 1$ level; (2) $v = 2 \rightarrow 1$ (*P*2) (overpopulating the $v = 1, J = 2$ level), and through $v = 1, J = 2 \rightarrow 1$, giving the SiO maser detected by Snyder and Buhl (1974) and overpopulating the $v = 1, J = 1$ level. Thus both photon routes (1) and (2) overpopulate the $v = 1, J = 1$ level, finally giving rise to the $v = 1, J = 1 \rightarrow 0$ SiO maser. This variation of the Geballe and Townes (1974) pumping scheme might be preferred over their proposed pumping mechanism, which utilizes strong coincidences within a single molecular spectrum, because it does not necessarily predict a CO maser; because it is supported by the high correlation between H_2O and SiO maser sources; and because it would not require every SiO infrared source to be also a maser source. This scheme predicts a weak $v = 1$, $J = 3 \rightarrow 2$ SiO maser, because the $v = 2$, $J = 3$ level is not directly pumped, but rather is inverted due to underpopulation of the $J = 2$ level; this underpopulation would be caused by a saturated $v = 2$, $J = 2 \rightarrow 1$ transition coupled with fast relaxation to $v = 0$ through the resonance pair $v = 1 \rightarrow 0$ ($R0$) + $v = 3 \rightarrow 2$ ($R18$), as suggested by Geballe and Townes (1974). One difficulty with this proposed pumping scheme is that the 1219.1 cm^{-1} H_2O line required to trigger the maser has been assigned as the $J_{K-K+} = 11_{66}{}'-12_{75}{}''$ of the ν_2 fundamental band (Benedict, Claasen, and Shaw 1952), and hence is very weak at temperatures of a few hundred degrees. In addition, there is some uncertainty about the frequency of this line; its calculated value is 0.1 cm^{-1} higher than the measured value. In laboratory spectra, the 1219.1 cm^{-1} H_2O line is blended with the stronger adjoining $J_{K-K+} = 6_{15}{}'-7_{44}{}''$ H_2O line of ν_2 at 1218.63 cm^{-1}. At temperatures between 500 K and 1000 K, where these two H_2O lines have roughly comparable intensities, it may be that they form a composite stellar spectral feature from about 1218.6 to 1219.2 cm^{-1}, and part of this blended feature is in close enough resonance with the SiO $2 \rightarrow 1$ ($R0$) to serve as a pump line. The SiO $v = 2$, $J = 2 \rightarrow 1$ maser may not be detectable because the SiO $v = 2 \rightarrow 1$ ($R1$) line at $\sim$1220.57 cm^{-1} is not close enough to either the proposed 1219.1 cm^{-1} H_2O pump line or the $J_{K-K+} = 11_{65}{}'-12_{76}{}''$ H_2O line in the ν_2 band, which has a measured frequency of 1220.43 cm^{-1} and a calculated frequency of 1220.60 cm^{-1} (Benedict *et al.* 1952). On the other hand, because of rest frequency uncertainties, the latter line could be in resonance with the SiO $2 \rightarrow 1$ ($R0$), but not of sufficient intensity to support inversion in the SiO $v = 2$, $J = 2$ level.

Mather and Litvak (1974) have proposed a pumping model which utilizes a continuum pump with collisions at high kinetic temperatures. In their model, radiation trapping reduces the infrared transition probabilities between the SiO vibrationally excited levels in proportion to the photon escape probabilities. All of the observed SiO maser transitions are predicted with the $v = 1$, $J = 2 \rightarrow 1$ and $1 \rightarrow 0$ transitions saturated; also, no masers in the $v = 0$ levels are predicted. This model also predicts that an SiO $v = 2$, $J = 2 \rightarrow 1$ maser can occur for certain temperatures, densities, and velocity gradients (but not necessarily at the same location as a $v = 1$ maser); however, this maser has not yet been detected.

An ultraviolet pumping scheme for the SiO maser has been suggested by Buhl *et al.* (1974). This would require ultraviolet absorption near 2257 Å followed by distribution over the $v = 1$, 2, and 3 levels in the ground electronic state. As pointed out by Buhl *et al.* (1974), this process predicts less specific vibrational excitation than the previously discussed infrared line or continuum pumps.

Finally, we believe that two topics concerning the maser mechanisms deserve further theoretical and observational treatment. First, the absence of an SiO maser in the ground vibrational state should be thoroughly established by more observations. As shown in figure 5, $v = 2 \rightarrow 1$ ($P2$) + $v = 1 \rightarrow 0$ ($R1$) tend to overpopulate the $v = 0$, $J = 1$ level. But $v = 2 \rightarrow 1$ ($P1$) + $v = 1 \rightarrow 0$ ($R0$) may provide a faster photon relaxation route due to the resonance between $v = 1 \rightarrow 0$ ($R0$) and $v = 3 \rightarrow 2$ ($R18$), as discussed by Geballe and Townes (1974), thus overpopulating the $v = 0$, $J = 0$ level and destroying the inversion necessary for a $v = 0$, $J = 1 \rightarrow 0$ maser. But this resonance would not have much direct effect on the $v = 0$, $J = 2$ level; hence we suggest that there may be sources where weak $v = 0$, $J = 2 \rightarrow 1$ maser emission can be detected. In particular, the $v = 0$, $J = 2 \rightarrow 1$ SiO transition in Ori A, detected by Dickinson (1972), presumably is a normal emission line, but its abnormally extended wings could be concealing weak maser emission features near 16 and -7 km s^{-1}. Thus this line should be examined again with higher spectral resolution. Second, we note that the SiO maser has only been found in M stars (except for χ Cyg, which is very similar to an M star), which may be only an observational selection effect. Auman's (1969) models of atmospheres of late-type stars always show a spike in the emitted flux which is located near 2400 cm^{-1}, or 0.24 μ^{-1}. The spike, caused by H_2O opacity at 0.38 μ^{-1}, is strongest at 2000 K in Auman's models, and fades out as the temperature approaches 4000 K and the dominant source of opacity changes from H_2O to the H^- ion. Since this $\sim$0.24 μ^{-1} spike in the emitted flux approximately coincides with the frequencies of the SiO overtone bands v = 2–0, 3–1, 4–2, etc., we suggest that it may pump the first SiO overtone (and possibly higher overtones), and effectively invert the SiO $v = 2$, $J = 1$ level (see fig. 5). Thus SiO masers would not be detected in sources hotter than $\sim$4000 K if this pumping mechanism is effective.

IV. CONCLUSIONS

The $J = 1 \rightarrow 0$ transition of SiO at 43,122.0 MHz has been found to be the most intense of the $v = 1$ transitions for the majority of stellar sources detected thus far. We suggest that a feasible future observational program would be to use this frequency to search obscured regions for undetected variable stars or to confirm suspected variable stars. A searchlight-type survey could concentrate on dusty, obscured regions of constellations where the suspected number of variable stars is high but the actual star count is low; see, e.g., Kukarkin *et al.* (1969) for a list of constellations with abnormally small numbers of variable stars. As discussed in § III*b*, it appears that when the observational statistics are more complete, it will be possible to use the SiO maser for approximate classification of stellar spectral and variable type. All of the classified stellar SiO masers in tables 1 and 2 are in the range M3–M9 spectral class and all are Mira, irregular, or semiregular variables.

We have not yet surveyed a large enough sample of maser sources to meaningfully study correlations (if any) between signal strength and source distance, but the fact that many of the detected sources are 1 kpc or closer suggests that the failure to detect SiO emission from known OH/H_2O/IR sources in several H II regions (Snyder and Buhl 1974; Kaifu *et al.* 1975) could be due to beam dilution. On the other hand, if beam dilution is not important, and if it can be convincingly shown that many of the OH/H_2O/IR sources associated with molecular clouds are *not* also SiO maser sources, then the absence of SiO maser emission could serve as a convenient indicator that particular OH/H_2O/IR sources are not associated with late-type stars and hence may be much younger, perhaps even protostellar in origin.

Finally, we stress the importance of making spectral line interferometric measurements of the SiO maser sources. These measurements will be important for determining the true brightness temperatures of the emission lines and for making source models which will permit detailed modeling of the maser mechanism.

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